

COLLECTIVE EFFECTS IN CENTRAL HEAVY-ION COLLISIONS

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Abstract. In-medium effects on transverse-mass distributions of quarks and gluons are considered assuming a possible local equilibrium for colorless quark objects (mesons and baryons) created in central A+A collisions. It is shown that the average transverse momentum squared for these partons grows and then saturates when the initial energy increases. Within the quark-gluon string model it leads to the colliding energy dependence of hadron transverse mass spectra which is similar to that observed in heavy ion collisions. Comparison with other scenarios is given.

Experimental detection of the quark-gluon plasma (QGP) phase and the mixed phase (MP) in A+A collisions is a nontrivial task because of smallness of the space-time volume of the hot and dense system and possible contributions of hadronic processes simulating signals of QGP and MP formation. Nevertheless, recent experimental study of the transverse-mass spectra of kaons from the central $Au + Au$ and $Pb + Pb$ collisions revealed an "anomalous" dependence on the incident energy. The effective transverse temperature (the inverse slope-parameter of the transverse mass distribution at the mid rapidity) increases fast with incident energy in the AGS domain [1], then saturates at the SPS energies [2] and increases again approaching the RHIC energy region [3]. In agreement with expectations [4–6] this saturation was assumed to be associated with the deconfinement phase transition and indication of the MP [7, 8]. The anomalous effective temperature behavior was quite successfully reproduced within a hydrodynamic model with the equation of state involving the phase transition [9]. However, this result is not very convincing since to fit data, the required incident-energy dependence of the freeze-out temperature should closely repeat the shape of the corresponding effective kaon temperature, and thereby the problem of the observed anomalous inverse-slope dependence is readdressed to the problem of the freeze-out temperature.

In this paper, we propose another way to introduce a collectivity effect in a nuclear system via some in-medium effect. We consider the temperature dependence of quark distribution functions inside a colorless quark-antiquark or quark-diquark system (like meson or baryon, h) created in the central A+A collisions. A contribution of this effect to transverse momentum spectra of hadron is estimated and it is shown that it results in larger values of the inverse slope parameter and, therefore, in broadening of the transverse mass spectra.

Let us assume the local equilibrium in a fireball of hadrons whose distribution

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function can be presented in the following relativistic invariant form:

$$f_h^A = C_T \{1 \pm \exp((p_h \cdot u - \mu_h)/T)\}^{-1} , \quad (1)$$

where p_h is the four-momentum of the hadron, the four-velocity of the fireball in the proper system is $u = (1, 0, 0, 0)$, the sign "+" is for fermions and "-" is for bosons, μ_h is the baryon chemical potential of the hadron h , T is the local temperature, and C_T is the T -dependent normalization factor. The distribution function of constituent quarks inside h which is in local thermodynamic equilibrium with the surrounding nuclear matter, $f_q^A(x, \mathbf{p}_t)$, can be calculated using the procedure suggested for a free hadron in Ref. [10], see details in Ref [11],

$$f_{qv}^A(x, p_t) = \int_0^1 dx_1 \int_0^1 dx_h \int d^2 p_{1t} d^2 p_{ht} \tilde{q}_v(x, \mathbf{p}_t) \tilde{q}_r(x_1, \mathbf{p}_{1t}) \times f_h^A(x_h, \mathbf{p}_{ht}) \delta(x + x_1 - x_h) \delta^{(2)}(\mathbf{p}_{1t} + \mathbf{p}_t - \mathbf{p}_{ht}) , \quad (2)$$

where $\tilde{q}_v(p_z, \mathbf{p}_t)$ is related to the probability to find a valence quark with longitudinal momentum p_z and transverse momentum \mathbf{p}_t in the hadron, whereas $\tilde{q}_r(p_{1z}, p_{1t})$ is the probability that all the other hadron constituents (one or two valence quarks plus any number of quark-antiquark $q\bar{q}$ pairs and gluons) carry a total longitudinal momentum p_{1z} and the total transverse momentum p_{1t} ; $x = 2p_z^*/\sqrt{s'}$, $x_1 = 2p_{1z}^*/\sqrt{s'}$, $x_h = 2p_{hz}^*/\sqrt{s'}$, where $p_z^*, p_{1z}^*, p_{hz}^*$ are the longitudinal momenta and s' is some characteristic energy squared scale.

The distribution of the hadron h in a fireball f_h^A is included in eq.(2), therefore we integrate over the longitudinal and transverse momenta of h . Assuming the factorization hypothesis $\tilde{q}_{v,r}(x, \mathbf{p}_t) = \tilde{q}_{v,r}(x) g_{v,r}(\mathbf{p}_t)$ and the Gaussian form for $g_{v,r}(\mathbf{p}_t)$, e.g., $g_{v,r}(\mathbf{p}_t) = \sqrt{\gamma_q/\pi} \exp(-\gamma_q p_t^2/2)$ we can get the following expression for $f_q^A(x, \mathbf{p}_t; T)$ normalized to 1 [11]:

$$f_q^A(x, \mathbf{p}_t; T) = \frac{1}{\pi} \int_0^{1-x} dx_1 \tilde{q}_v(x) \tilde{q}_r(x_1) \tilde{\Gamma}_q(x_1 + x) \exp(-\tilde{\Gamma}_q(x_1 + x) p_t^2) \quad (3)$$

where

$$\tilde{\Gamma}_q(x_h) = \frac{\gamma_q(1 + \gamma_q \tilde{m}_h(x_h)T/2)}{1 + \gamma_q \tilde{m}_h(x_h)T} \quad (4)$$

and $\tilde{m}_h(x_h) = \sqrt{m_h^2 + x_h s'/4}$. Then the averaged transverse momentum squared for the quark at $x \simeq 0$ in a locally equilibrated hadron is

$$\langle p_{q,t}^2(x \simeq 0) \rangle_{h,appr.}^A \simeq \frac{\langle p_t^2 \rangle_q^h + T \sqrt{m_h^2 + s'/4}}{1 + T \sqrt{m_h^2 + s'/4} / (2 \langle p_t^2 \rangle_q^h)} , \quad (5)$$

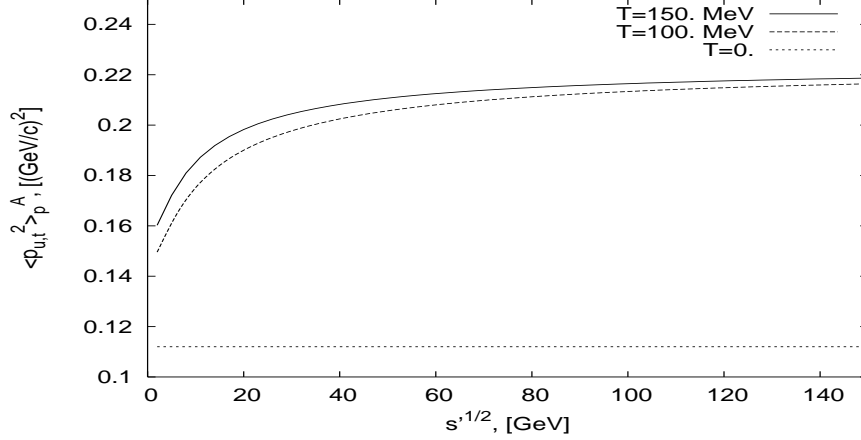


Figure 1: The energy dependence of the average transverse momentum squared for the u -quark in a proton in nuclear matter at temperature T .

where $\langle p_t^2 \rangle_q^h$ is the transverse momentum squared for the quark in a free hadron. More accurate calculational results for this quantity of the u quark in a proton $\langle p_{u,t}^2(x \simeq 0) \rangle_p^A$ are presented in Fig.1.

Let us estimate now the p_t distribution of hadron h_1 produced from a collision of two hadrons h inside the fireball. We shall explore the quark-gluon string model (QGS) [16,17] or the dual parton model (DPM) [18] based on the $1/N$ expansion in the QCD [14,15].

To calculate the transverse momentum spectrum of hadron h_1 in the mid rapidity region, one needs to know the p_t -dependence of the fragmentation function $D_q^{h_1}$. We assume the Gaussian dependence for $D_q^{h_1}$ like as for $\tilde{g}_{v,r}(p_t)$. However, the slope of this p_t -dependence γ_c can differ from the slope γ_q for constituent quark p_t -distribution

$$\langle p_{h_1,t}^2 \rangle_{NN,appr.}^{AA} \simeq \frac{\langle p_t^2 \rangle_q^N + T\sqrt{m_N^2 + s_{hh}/4}}{1 + T\sqrt{m_N^2 + s_{hh}/4} / (2\langle p_t^2 \rangle_q^N)} + \frac{\langle p_t^2 \rangle_q^N}{r}, \quad (6)$$

where s' has been associated with the energy squared s_{hh} of colliding hadrons and $r = \gamma_c/\gamma_q$. Note, that $\sqrt{s_{hh}}$ is not related directly to the initial energy of colliding heavy ions.

We estimated the average value of transverse momentum squared for K^+ -mesons produced in the nucleon-nucleon $\langle p_{K^+,t}^2 \rangle_{NN}^{AA}$ and pion+nucleon $\langle p_{K^+,t}^2 \rangle_{\pi N}^{AA}$ interactions in a fireball created in the central $A-A$ collision as a function of $\sqrt{s_{hh}}$ at $T = 150 MeV$ for two cases when $\gamma_c \gg \gamma_q$ and $\gamma_c = 3\gamma_q$ [19]. In Fig.2, the curves 1 and 2 correspond to $\langle p_{K^+,t}^2 \rangle_{NN}^{AA}$ and

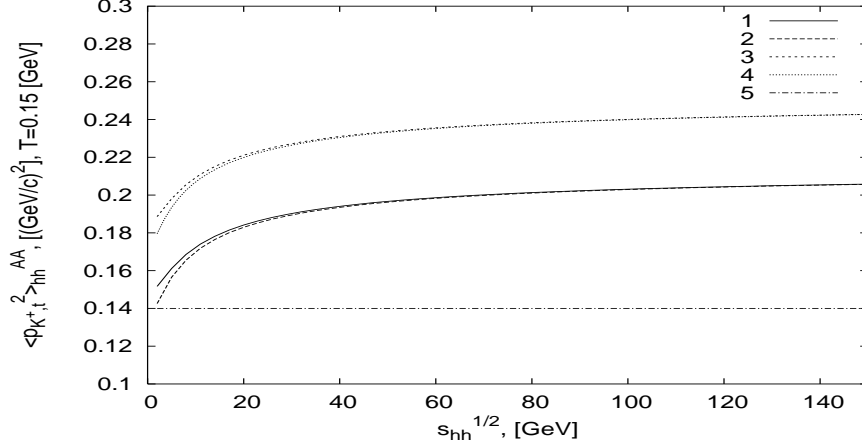


Figure 2: Average square for the transverse momentum of K^+ -meson produced from the interaction of two hadrons one of them is in the equilibrated fireball as a function of $\sqrt{s_{hh}}$ at $T = 150$ MeV.

$\langle p_{K^+,t}^2 \rangle_{\pi N}^{AA}$, respectively, when $\gamma_c \gg \gamma_q$, whereas the curves 3 and 4 correspond to the same quantities with $\gamma_c = 3\gamma_q$. The line 5 in Fig.2 corresponds to the average square for the transverse momentum of K^+ produced in the free $p + p$ collisions $\langle p_t^2 \rangle_{K^+}^{NN} = 0.14 \text{ GeV}/c^2$. As our calculations show, the temperature dependence for $\langle p_{K^+,t}^2 \rangle_{hh}^{AA}$ is rather weak in the interval $T = 100 - 150$ MeV.

As is evident from Fig.2, the obtained results are sensitive to the mass value of a hadron which is locally equilibrated with the surrounding nuclear matter at $\sqrt{s_{hh}} \leq 10(\text{GeV})$.

We found that the quark distribution in a hadron depends on the fireball temperature T . At any T the average transverse momentum squared of a quark grows and then saturates when $\sqrt{s_{hh}}$ increases. Numerically this saturation property depends on T . It leads to a similar energy dependence for the average transverse momentum squared of hadron h_1 $\langle p_{h_1,t}^2 \rangle_{hh}^{AA}$. The saturation property for $\langle p_{h_1,t}^2 \rangle_{hh}^{AA}$ depends also on the temperature T and it is very sensitive to the dynamics of hadronization. As an example, we studied the energy dependence of the inverse slope of transverse mass spectrum of K -mesons produced in central heavy-ion collisions and got its energy dependence qualitatively similar observed to one experimentally. We guess that our assumption on the thermodynamical equilibrium of hadrons given by eq.(1) can be applied for heavy nuclei only and not for the early interaction stage.

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